Gas-filled Cylindrical Liner Experiments on MAGPIE

Outline of experiment

Laser probing *in*
Optical emission *out* to spectrometer

Liner
with Ar/Xe gas inside

Glass windows

Mirror

Laser probing out
Optical emission *out* to streak camera

Anode

Cathode
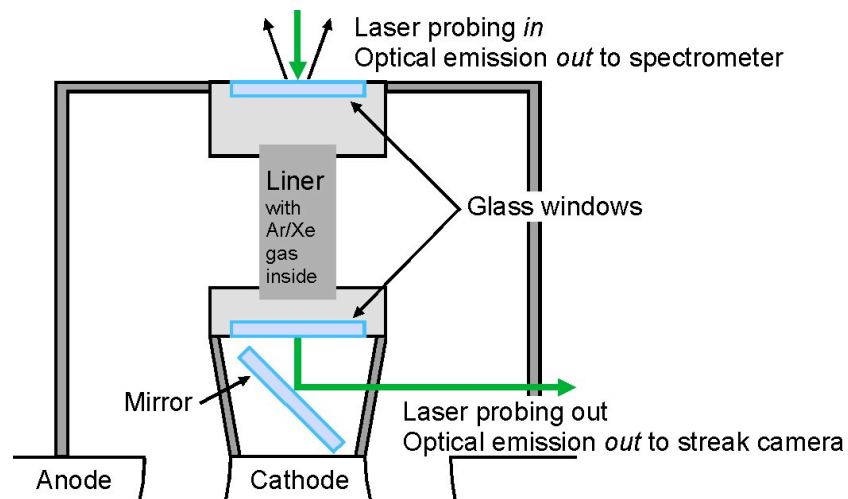
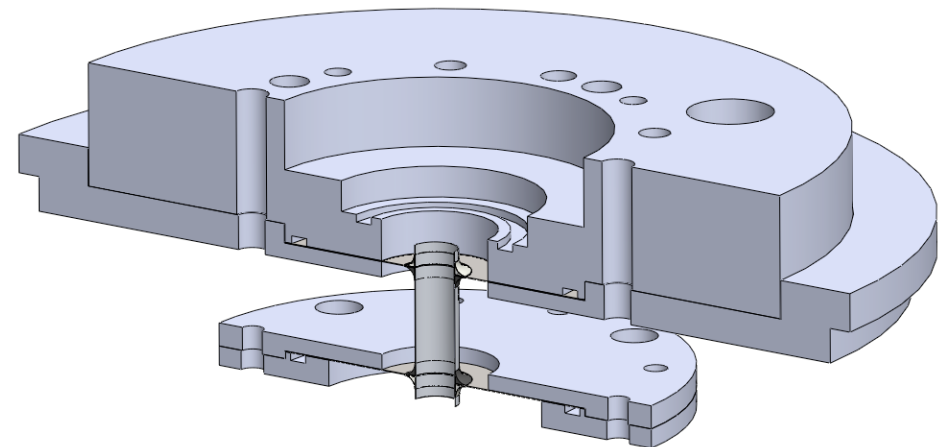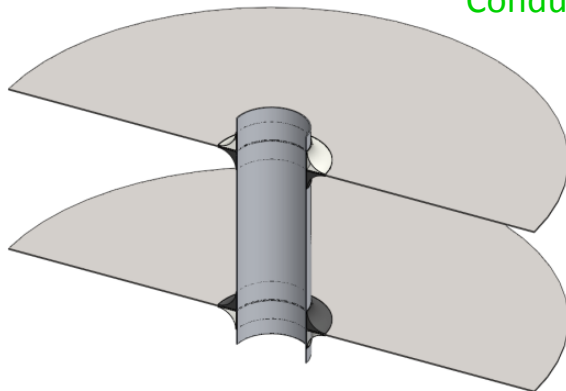System is **diagnosed 'end-on'** along the liner axis

- 355nm (UV) and 532nm interferometry and
   Schlieren imaging
- Optical streak photography
- Optical spectroscopy

Electrical contacts to load hardware

14mm

Liner

Conducting silver paint

Epoxy

Outline of experiment

1.4 MA, 250 ns current pulse is delivered to a **gas-filled cylindrical liner**

Aluminium Liners

6 mm diameter, 80 um wall
Aspect Ratio = 40
14 mm long
Al 6061
$\delta_0 = \sqrt{(2\rho/\mu)} = 60um$

- Multiple shocks driven into gas from inner liner surface

- Shocks are radiative – evidence for precursor

- No bulk motion of the liner wall

- No plasma seen on outer liner surface

Gas	$\rho = 1.2e^{-6}$ g/cc	$\rho = 6e^{-6}$ g/cc	$\rho = 1.3e^{-5}$ g/cc
Argon (A=40, Z=18)	0.7mBar (1.8e16atoms/cc)	--	8mBar (2e17atoms/cc)
Xenon (A=131, Z=54)	--	1.1mBar (2.7e16atoms/cc)	2.5mBar (6e16atoms/cc)
Nitrogen (A=14, Z=7)	--	--	15mBar (N_2) (7.3e17 atoms/cc)

Results (i) Shock dynamics in gas-filled cylindrical aluminium liners

Dynamics from optical streak camera

1st shock - almost linear trajectory. **V = 20 km/s**. Blow-off from inner surface of liner is pushing into cold, neutral argon gas, ionising and heating it.

2nd shock is launched into heated, ionised argon. **Accelerating trajectory** may indicate presence of current and B field inside the liner.

s0812_11
8mBar Ar

Green 182ns
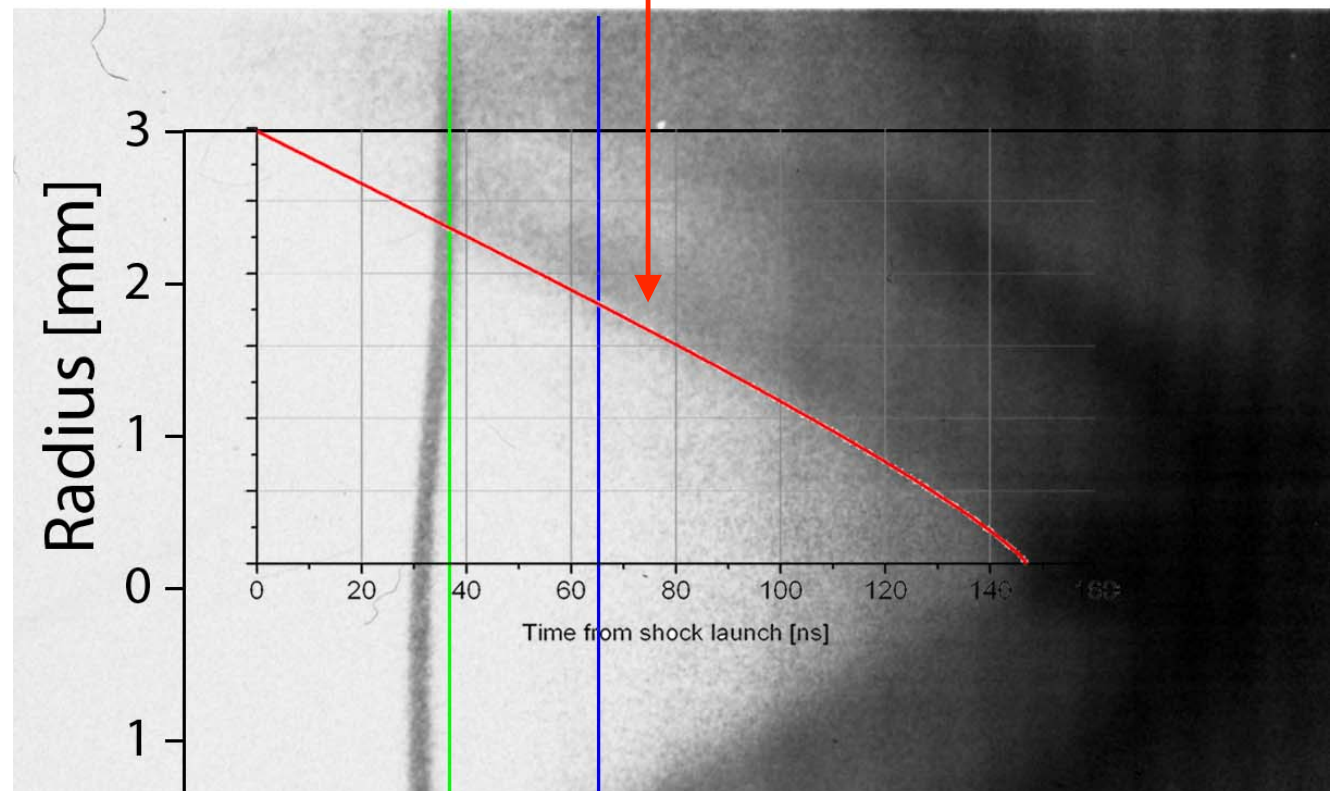(timing of the 2 laser frames)   Blue 210ns
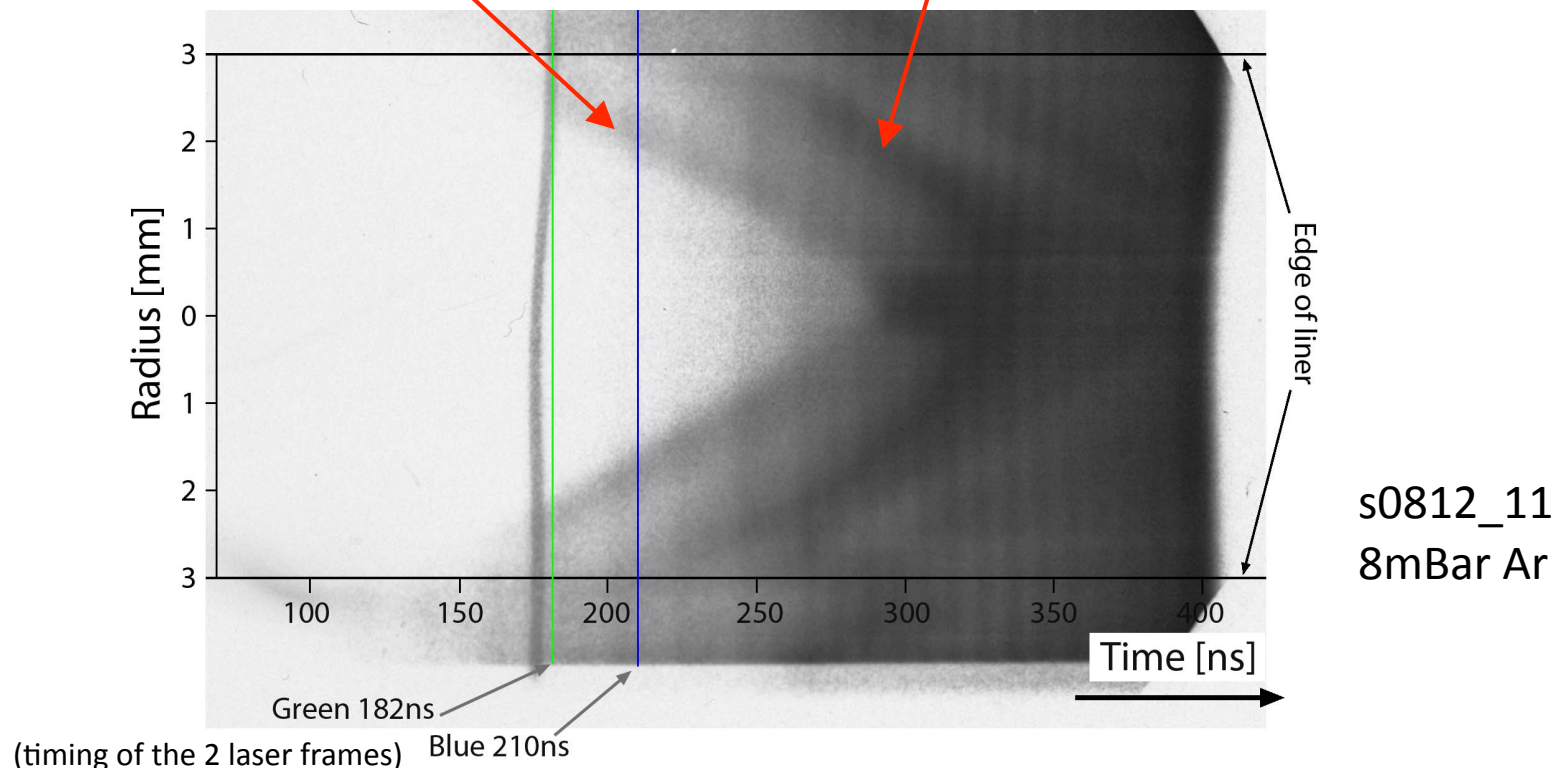
Shock trajectories

1st shock trajectory consistent with analytic solution (red line) for converging shocks caused by a cylindrical piston motion (Guderley, 1942):
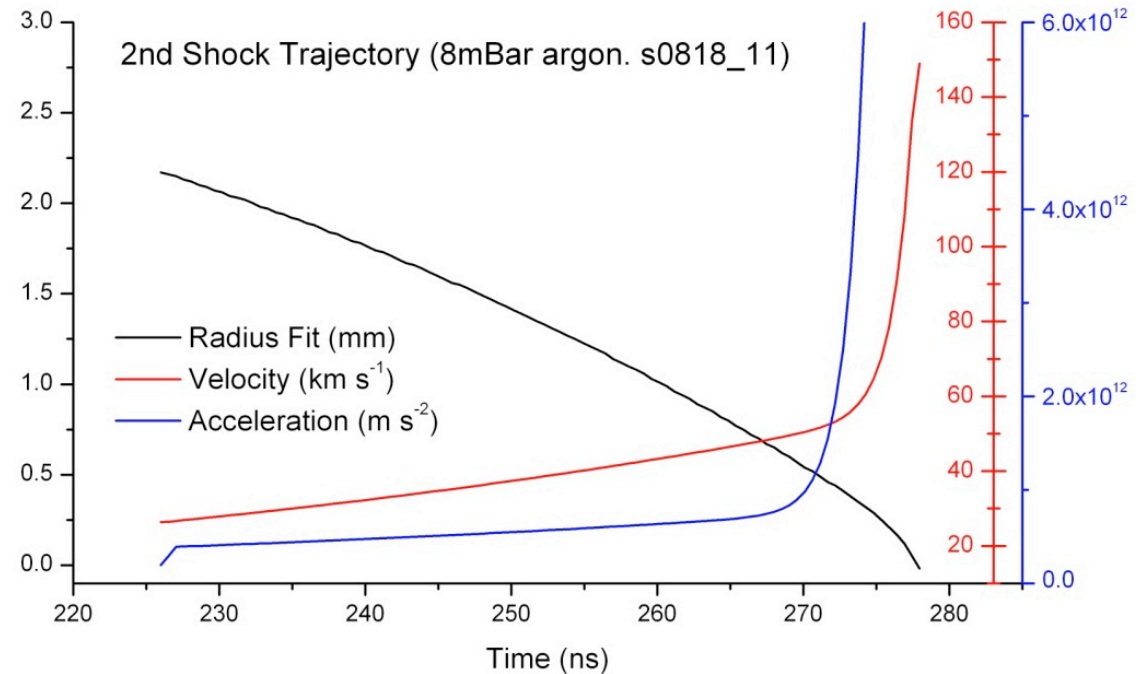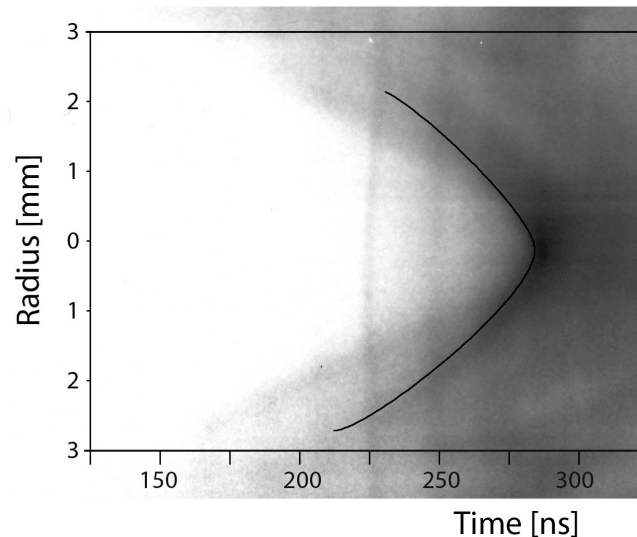
$$R(t) \approx \sum_{i=1} A_i \left(1 - \frac{t}{t_c} \right)^{\alpha_i}$$

Slight acceleration due to converging geometry.

Shock trajectories

Second shock shows more acceleration; driving force could be magnetic field.

2nd Shock Trajectory (8mBar argon. s0818_11)

— Radius Fit (mm)
— Velocity (km s^{-1})
— Acceleration (m s^{-2})

Estimate of current in gas

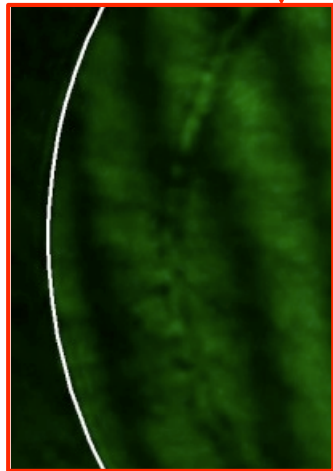Mass is assumed to occupy a thin shell and is estimated from interferometry line-outs
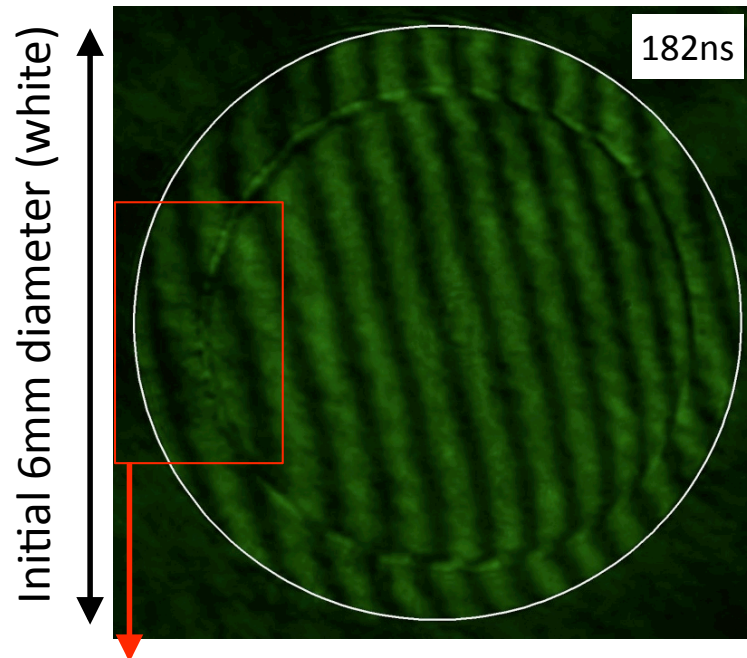
Then, use   *F = Magnetic Pressure x Area enclosing shell = ma*

Assuming electron density is due to singly ionised argon atoms, current required for observed acceleration at 253ns is approx. 50 kA
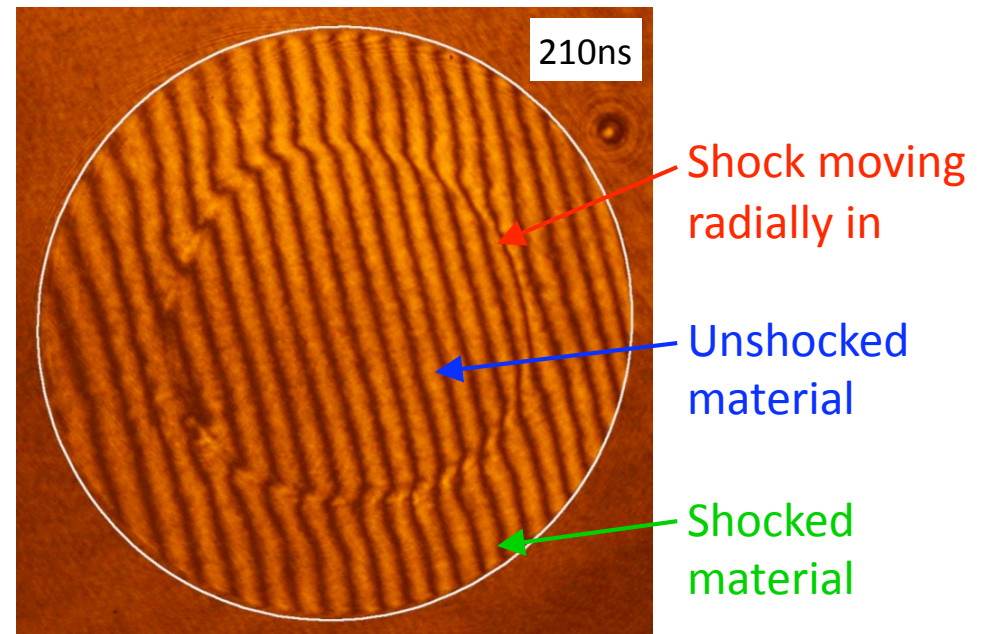
1st shock interferometry (Ar)

There are **two interferometry frames per shot**. One 532nm (green images) and one 355nm (orange images). The inter-frame time is 28ns on all shots.

Data from 8mBar argon shot. s0812_11

Initial 6mm diameter (white)

182ns

210ns

Shock moving radially in

Unshocked material

Shocked material

Shadowgraphy effect shows up shock structure

Changes in electron *and* neutral atom line density shift the interference fringes (in opposite directions)

532nm probe is 10X more sensitive to n_e

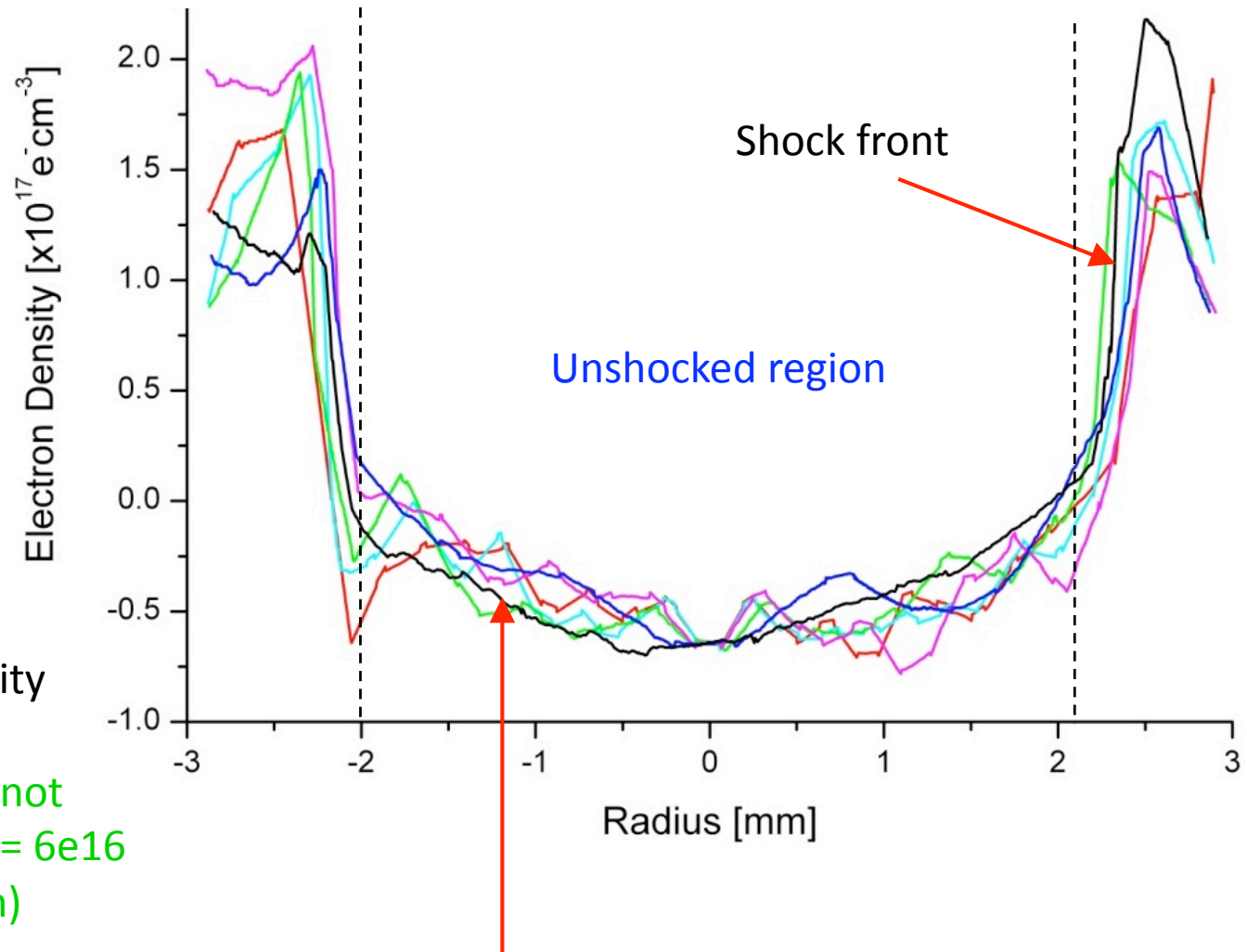355nm probe is 5X more sensitive to n_e

1ˢᵗ shock interferometry (Ar)

Electron density map from 532nm
frame and position of line-outs

Line-outs from 532nm electron density map

Shock front

Unshocked region
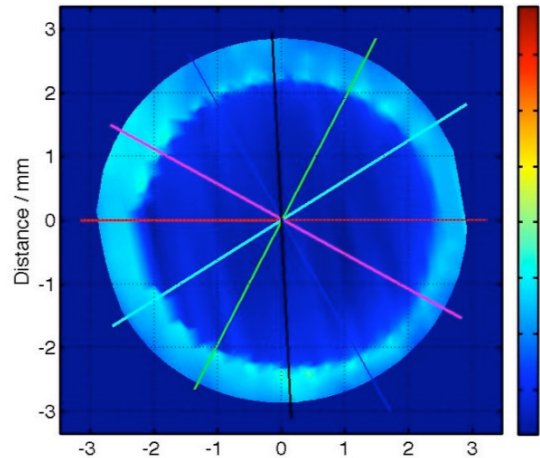
Initial n_{atom} = 2e17 cm⁻³

- matches peak electron density

Position of zero fringe shift is not
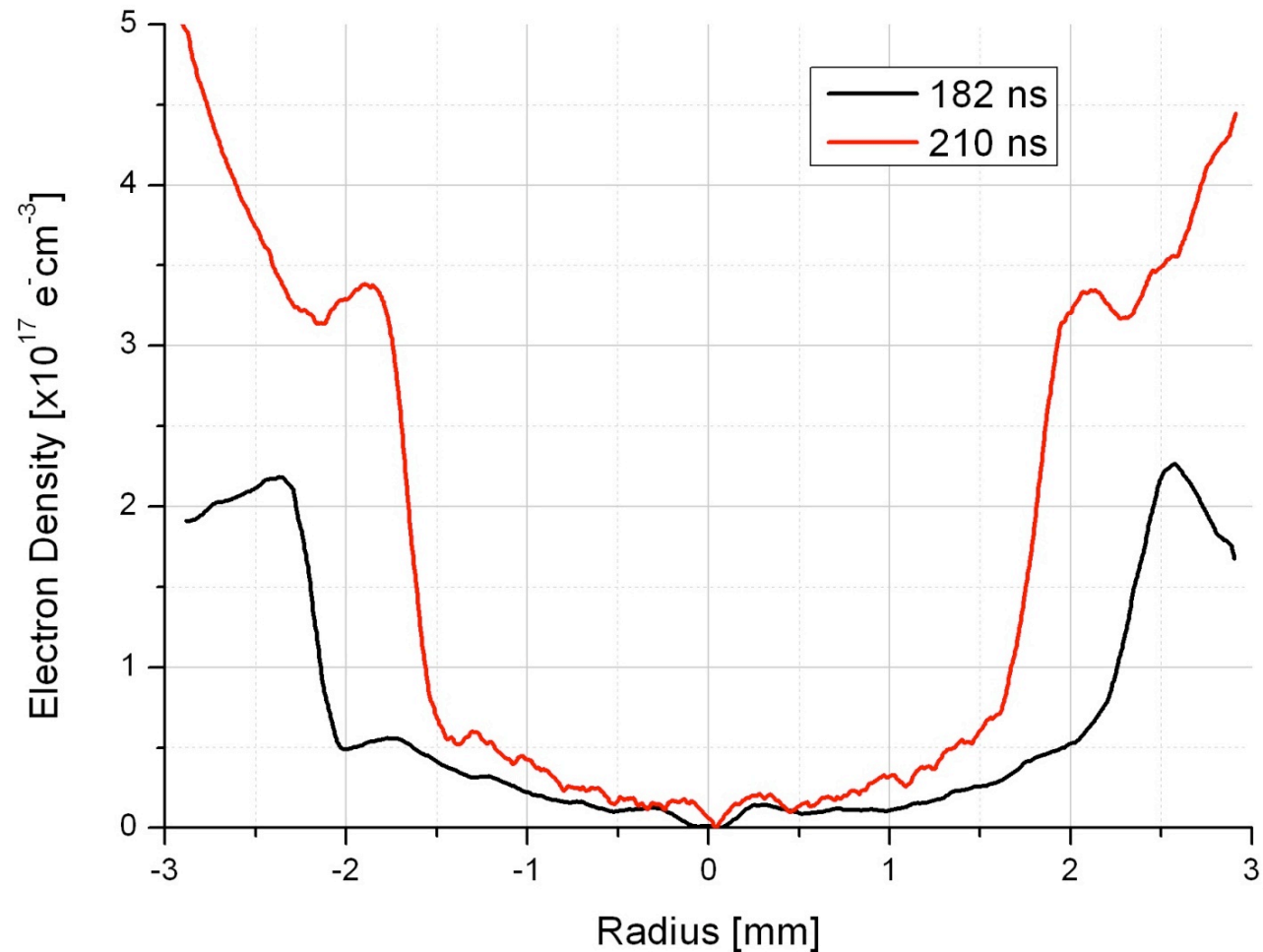known (1 fringe shift gives n_e = 6e16
cm⁻³ for 532nm, 14mm length)

Curved electron density profile in unshocked region – radiative precursor
Consistent with condition for radiative effects $\sigma T_S^4 > \rho_0 u_S^3 / 2$

1st shock interferometry (Ar)

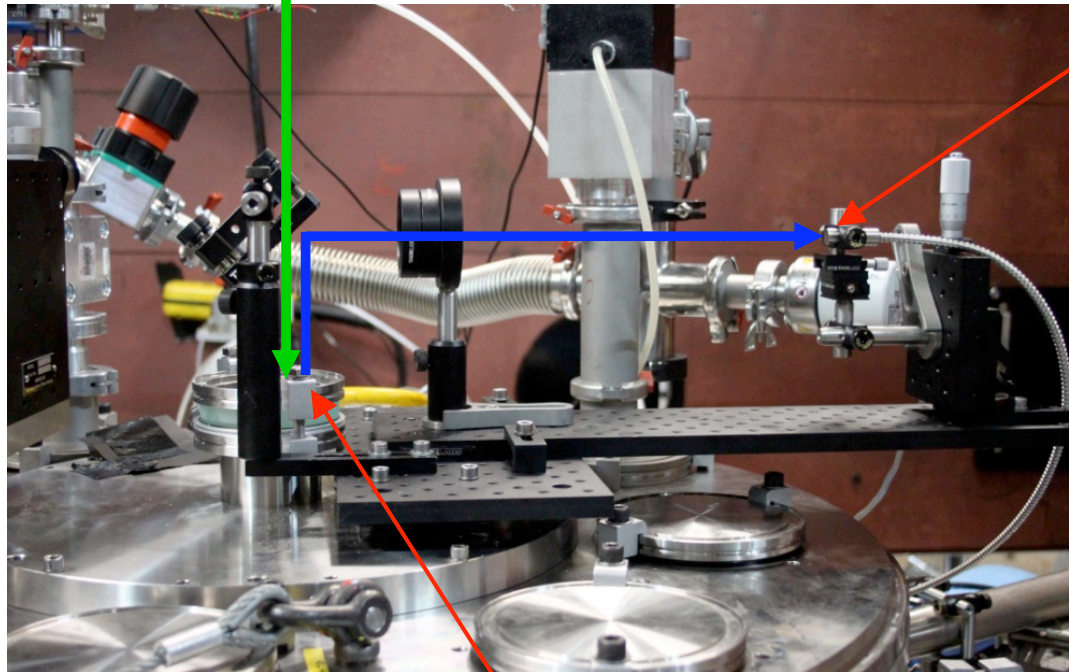**Azimuthally-averaged radial electron density profiles**

- Axial density has been set to zero. Absolute n_e changes for each lineout remain correct
- Precursor is seen
- Peak electron density increases as shock propagates

Optical spectroscopy

End-on view of liner is imaged onto a 7-fibre bundle and fed to an Andor ½ m spectrometer

Laser probing in

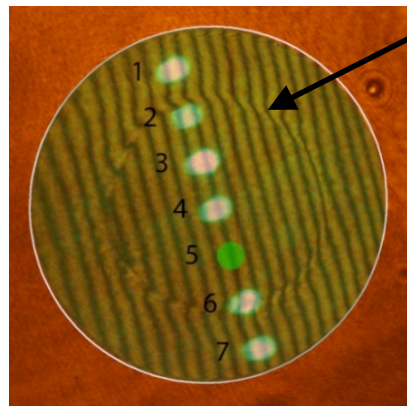Fibre bundle

Optical emission *out*

Axial window on chamber lid

300 lines/mm grating used to give broad range of wavelengths

Corresponding 1nm spectral resolution

Spatial resolution of 800um from opening angle of collecting lens
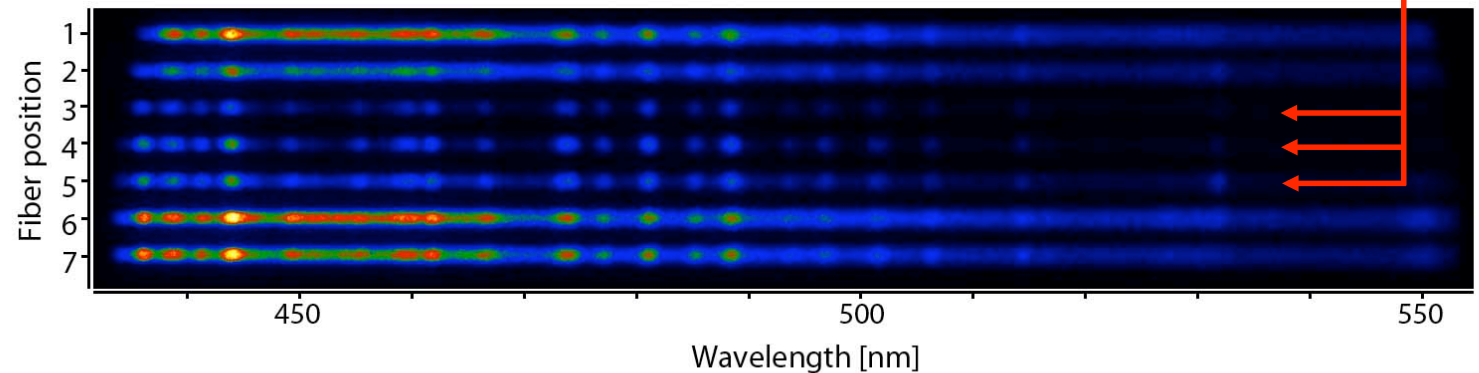
Optical spectroscopy

Argon fill (8mBar. S0812_11)

1st shock, yet to reach axis

Fibres 3, 4 and 5 should collect light from inside the radius of the shock

Position of fibres

Fiber position / Wavelength [nm]

Majority of lines appear to be ArII
Could be seeing preheating of the unshocked region by radiation from the shock front
Little evidence for Al emission – it is cold and/or there is not much of it

Theoretical post-shock temperature of 2eV given by agrees with spectroscopic data

$$k_B T_S = \frac{2(\gamma - 1)}{(\gamma + 1)^2} u_S^2 \cdot \frac{A m_p}{(Z + 1)}$$ (P. Drake)
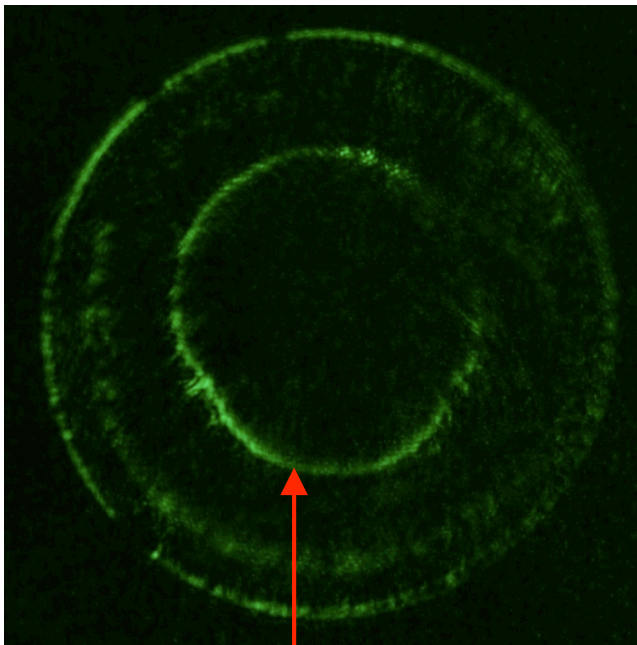
Same general picture when looking at 1st shock in xenon
Later time spectroscopy (of second shock) shows a lot of continuum emission

Schlieren imaging

Schlieren technique is good for imaging the sharp density gradients that occur at shock fronts
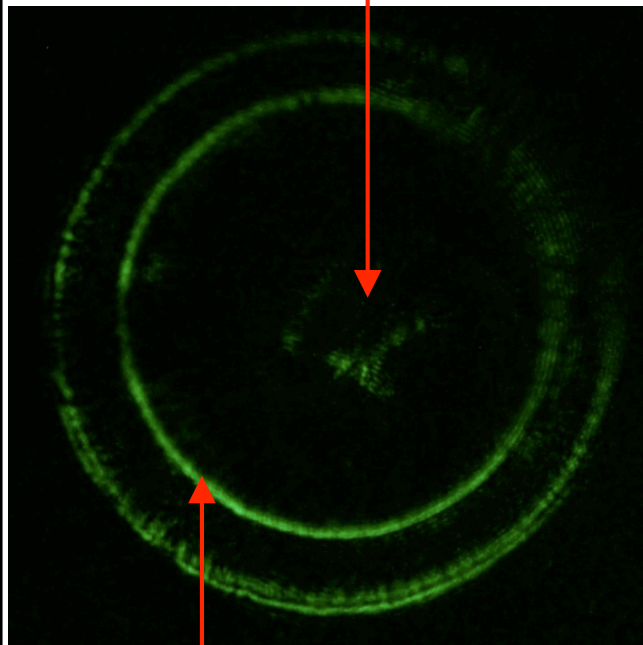
1st shock about to reach the axis not imaged well for the lower initial gas density in this shot

Material already on axis is not well imaged

8mBar argon s0818_11

1.1mBar xenon s0823_11

1st shock imaged clearly in 8mBar Ar

2nd shock is very uniform
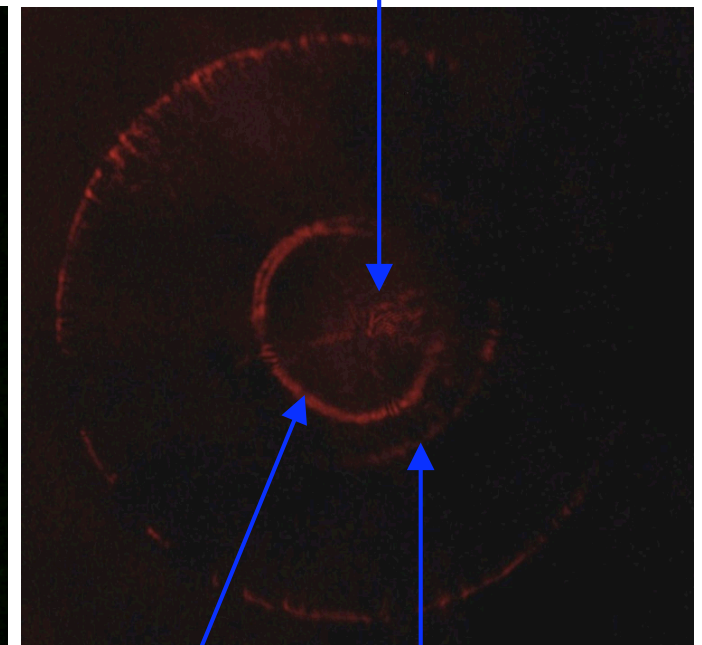
2nd shock
3rd shock? (not seen on streak)

Changing the mass density of the gas

Decreased the mass density of the gas inside to increases the speed of the shocks - more likely to see radiative effects.
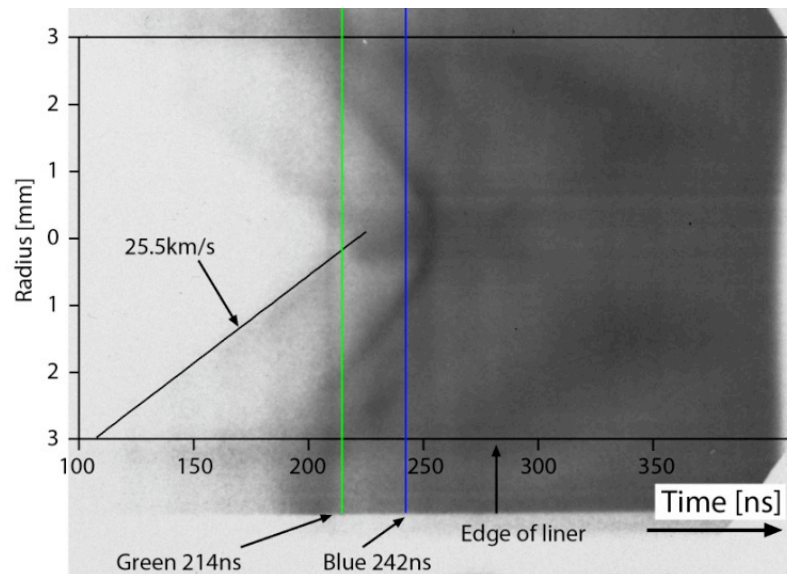
BUT – Shock speed not a strong function of gas density.

System gets difficult to diagnose at low densities as there is less emission and the sensitivity of the interferometer and Schlieren systems is reduced.

0.7mBar Ar. s0810_11
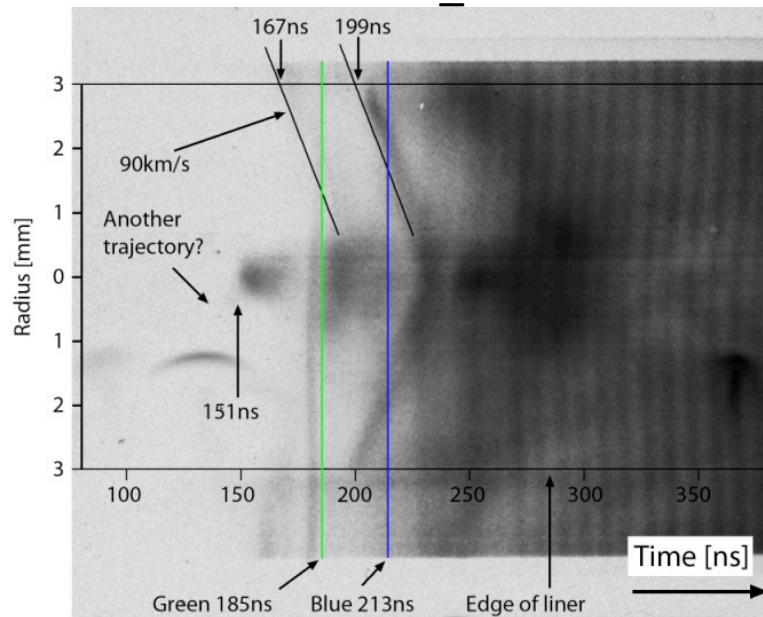
1.1mBar Xe. s0823_11

Shock speed hardly changes when mass density is halved.

Introduce axial magnetic field?

Ram pressure of shock given by $P_{ram} = \rho v^2$

For 1st Ar shock P_{ram} = 100 Bar
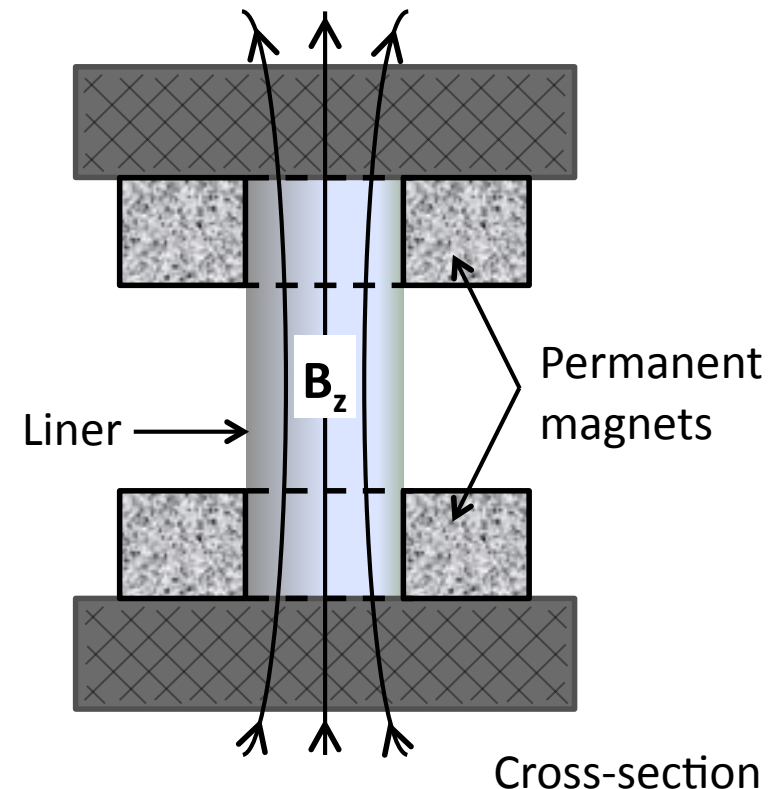For 2nd Ar shock P_{ram} = 1.6 kBar

Magnetic pressure given by $P_{mag} = \dfrac{B^2}{2\mu_0}$

For $P_{mag} = P_{ram}$

B = 5 T (1st shock)
B = 20 T (2nd shock)

$B \approx$ 1 T possible with permanent magnets

B_z

Liner

Permanent magnets

Cross-section

Results (ii)
Shock timing and current profile

Timing of 1st shock

Shot	1st shock timing ns	Current start ns	Rise ns	Peak current MA	Average dI/dt kA/ns	I(t_shock) MA
s0812_11	150	1552	240	1.20	5.00	0.78
s0815_11	127	1560	233	1.10	4.72	0.65
s0816_11	208	1444	336	1.07	3.18	0.63
s0817_11	180	1463	279	1.24	4.44	0.82
s0818_11	149	1550	246	1.21	4.92	0.80
s0819_11	263	1445	313	1.01	3.23	0.94
s0822_11	145	1545	242	1.16	4.79	0.74
s0823_11	98	1535	240	1.30	5.42	0.49
s0825a_11	202	1520	253	0.95	3.75	0.83
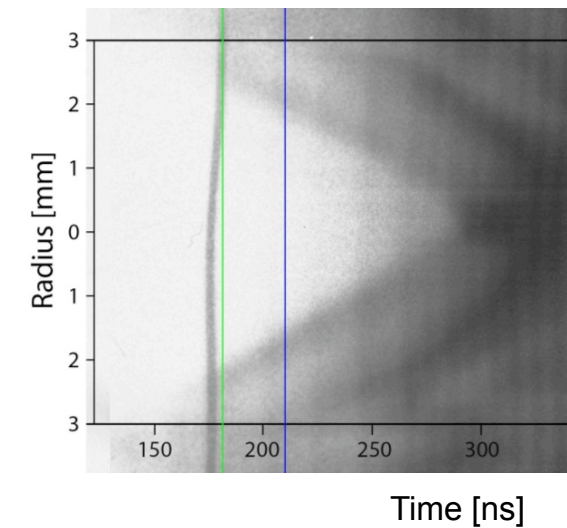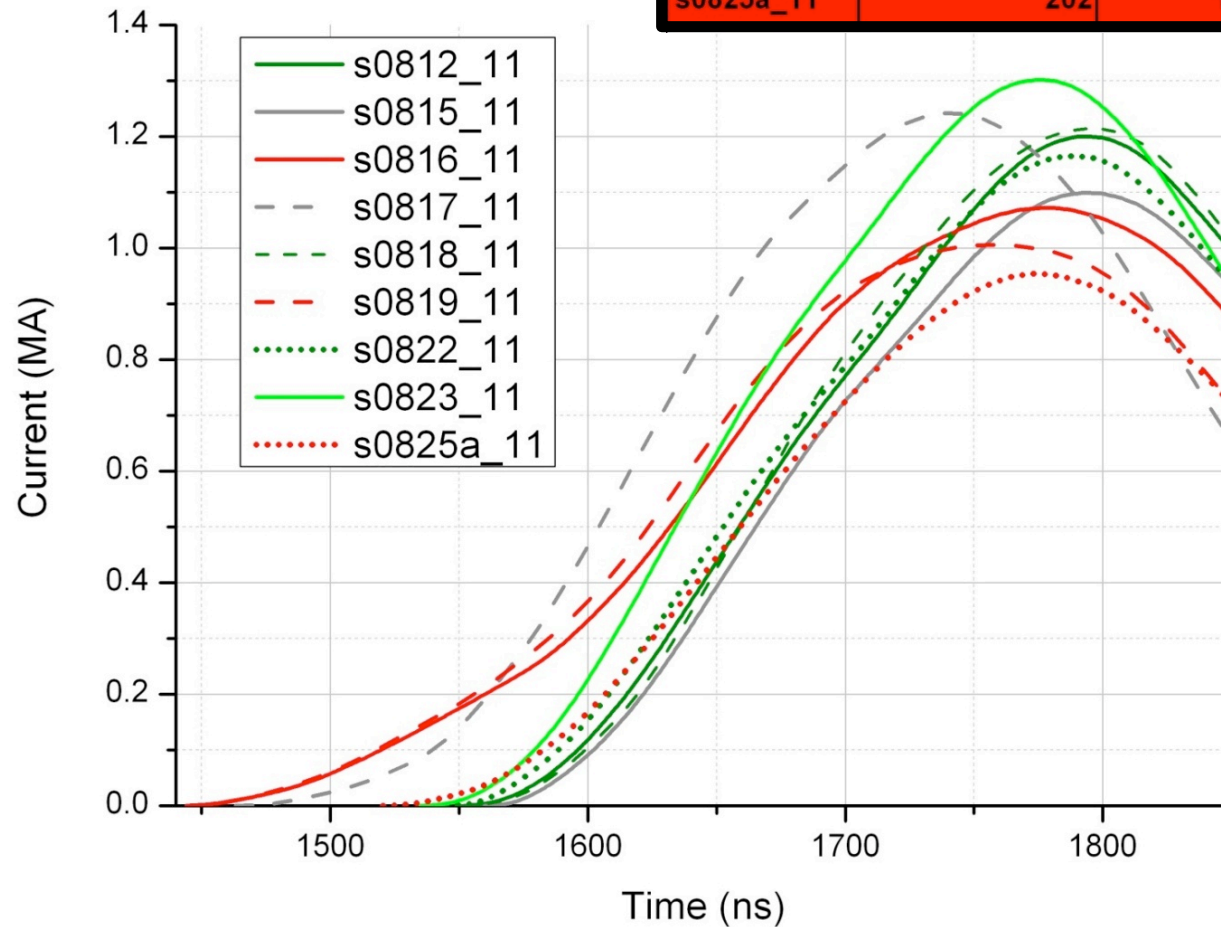
Timing of 1ˢᵗ shock
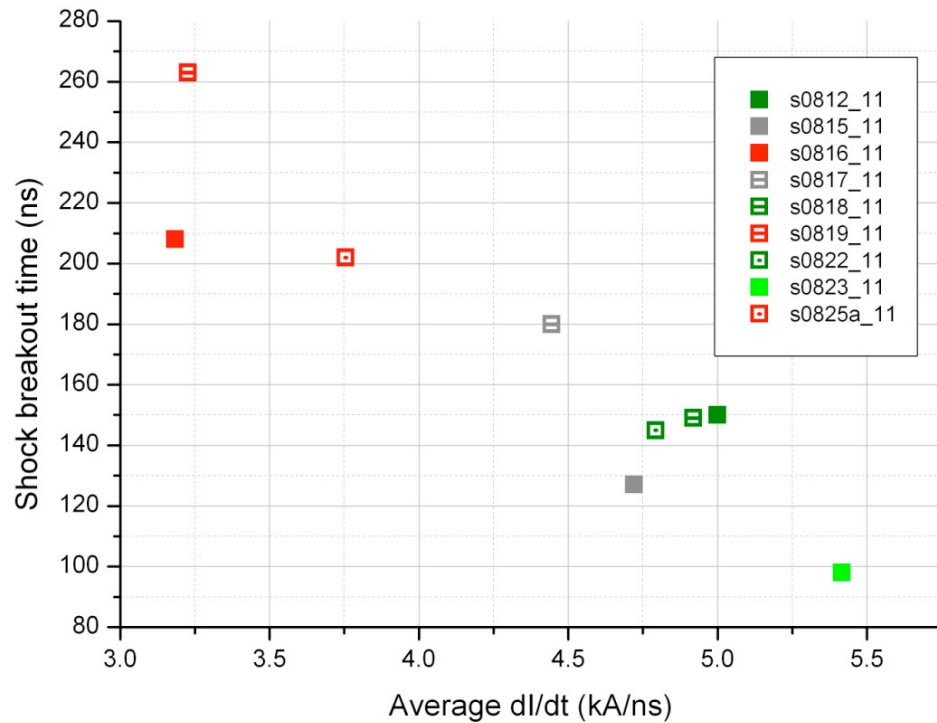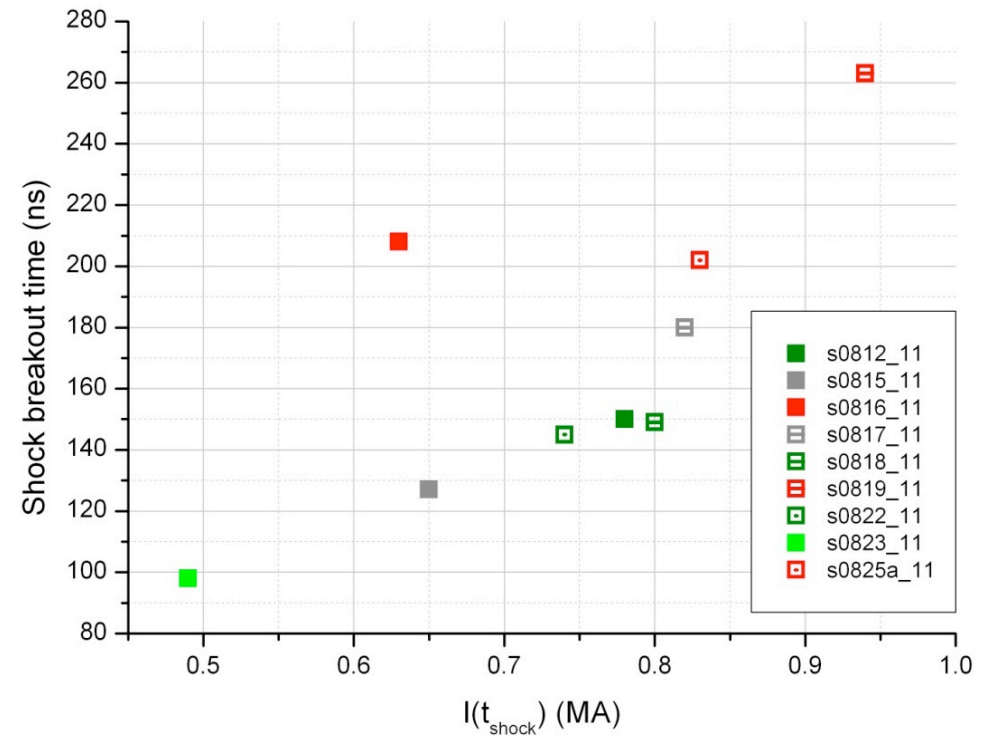
Timing of 1st shock

Current integral:

$$J = \int_0^t j^2 dt = \int_{Q_0}^{Q_f} \sigma \, dt$$

For Al:

$$J_{solid}^{melt} = 0.32 \times 10^{17} \, \mathrm{A^2 s \, m^{-4}}$$

$$J_{liquid}^{melt} = 0.40 \times 10^{17} \, \mathrm{A^2 s \, m^{-4}}$$

$$J_{liquid}^{boil} = 0.59 \times 10^{17} \, \mathrm{A^2 s \, m^{-4}}$$

$$J_{vapor}^{boil} = 1.09 \times 10^{17} \, \mathrm{A^2 s \, m^{-4}}$$

(Knoepfel, Wiley)
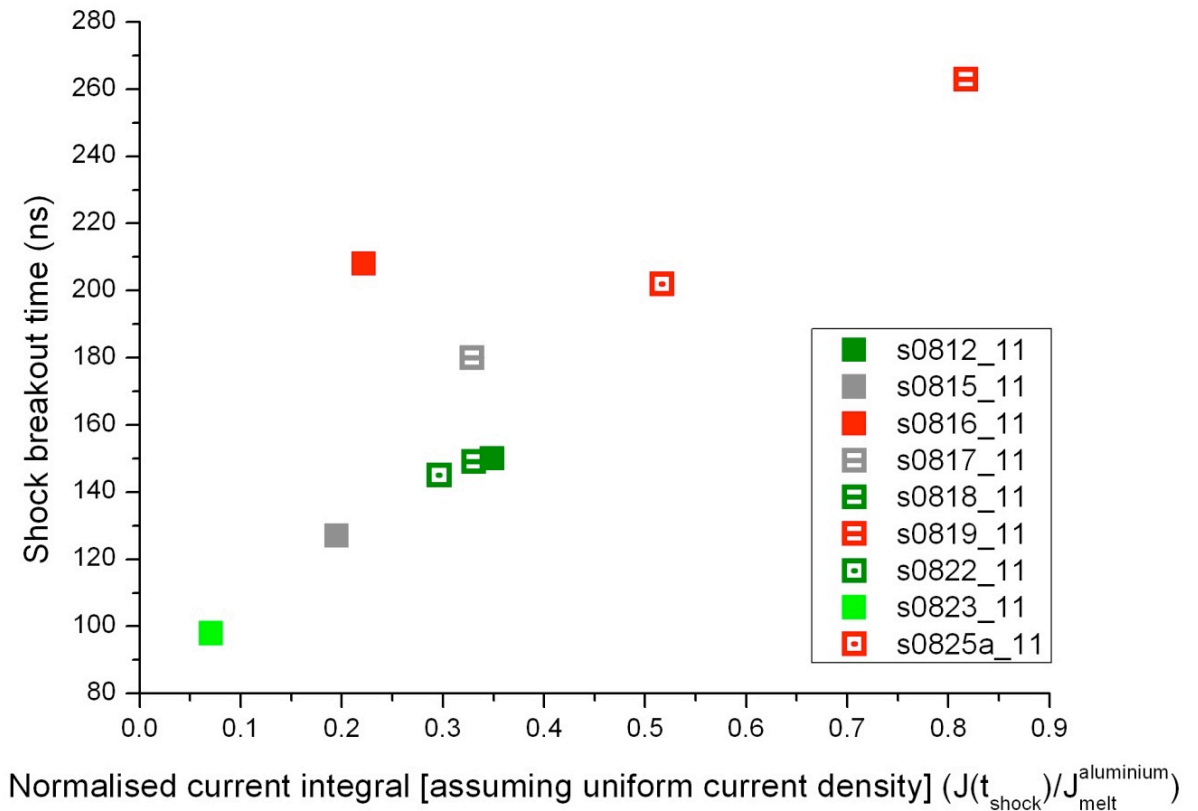
Calculated current integral at t_shock from measured current signal

Assumed uniform current density

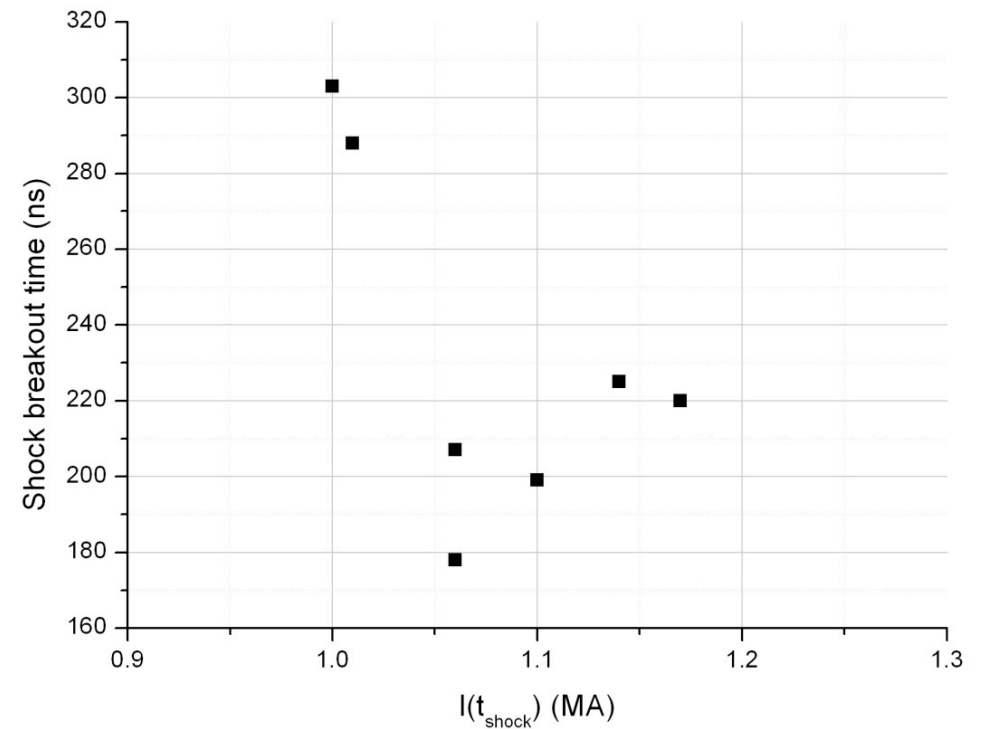Normalised to J_{solid}^{melt}
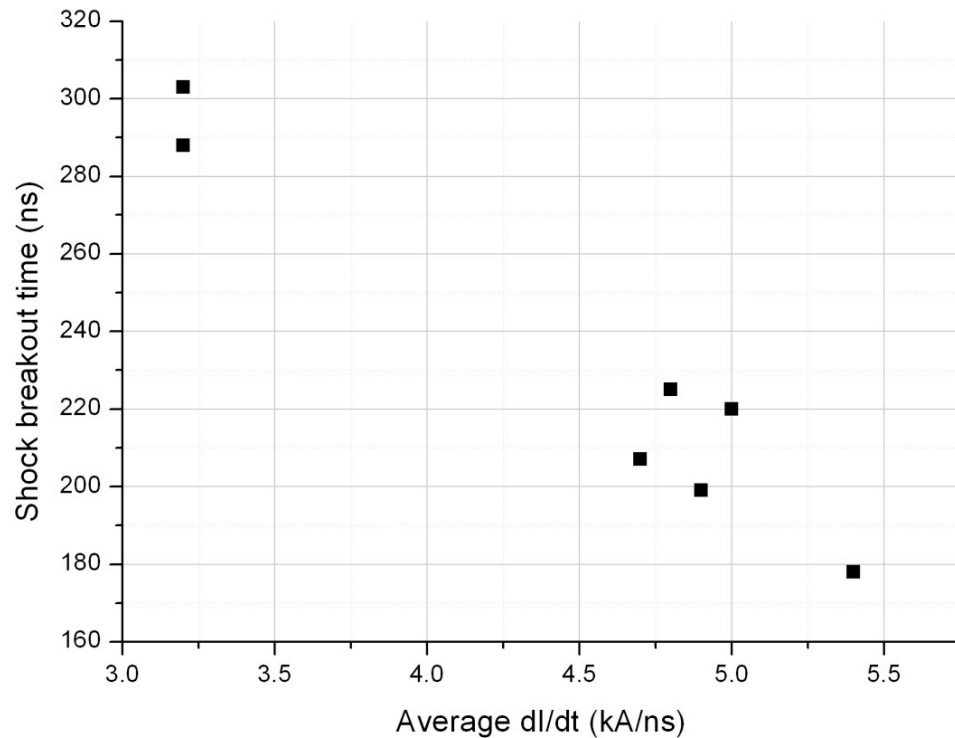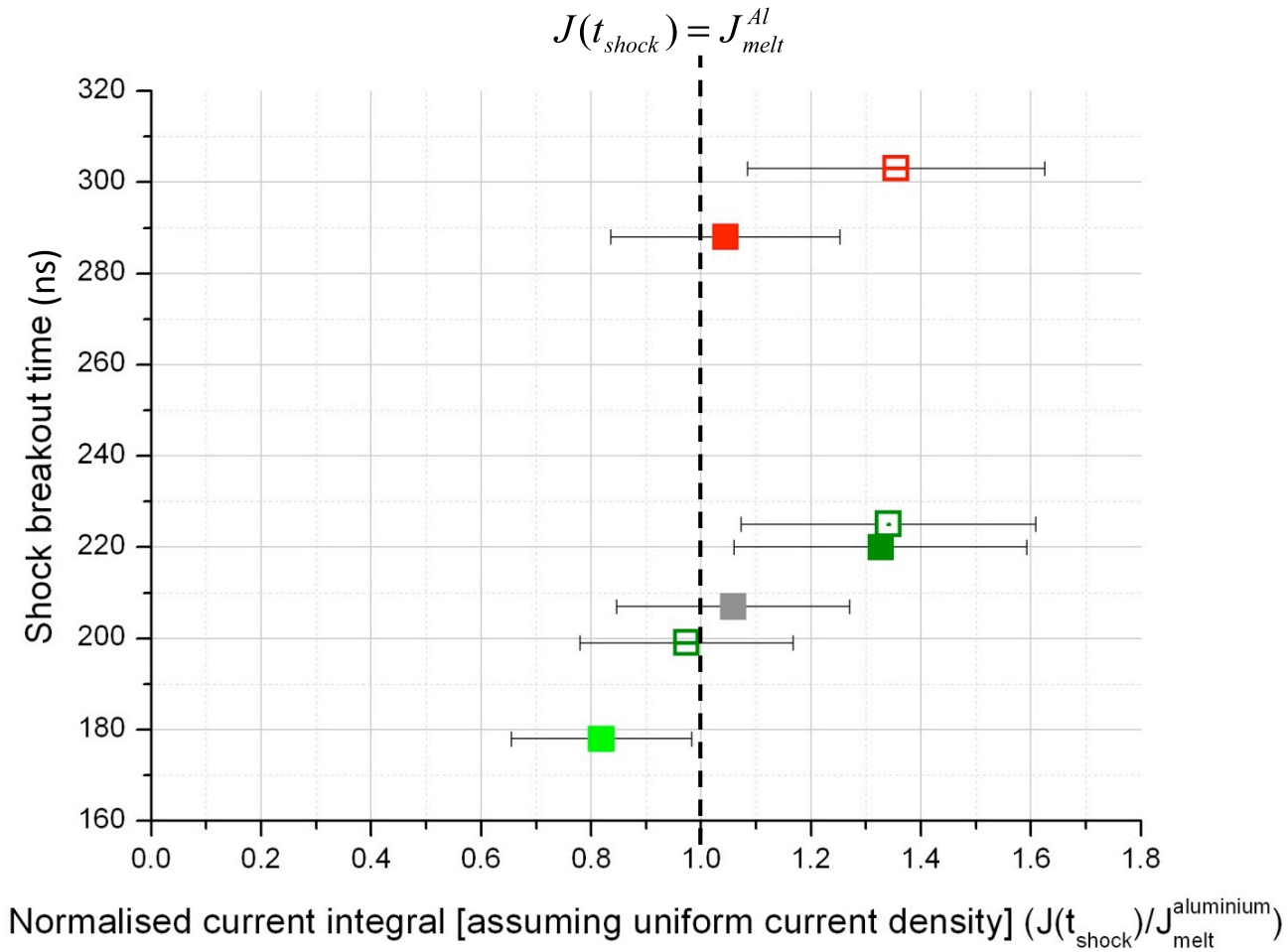
Timing of 2nd shock

Timing of 2nd shock

Current integral for 2nd shock

Results (iii)

Observations of outer liner surface

Outline of experiment

1.4 MA, 250 ns current pulse is delivered to a **cylindrical liner**

Aluminium Liners

6 mm diameter, 80 um wall

Al 6061

$\delta_0 = \sqrt{2\rho/\boxed{\text{⚡}}\mu} = 60um$

Homemade Aluminium Liners

10/14 mm diameter, 20 um wall

Al kitchen foil

$\delta_0 = \sqrt{2\rho/\boxed{\text{⚡}}\mu} = 60um$

Nickel Liners

3.6 mm diameter, 50 um wall

$\delta_0 = \sqrt{2\rho/\boxed{\text{⚡}}\mu} = 90um$

Electrical contacts to load hardware
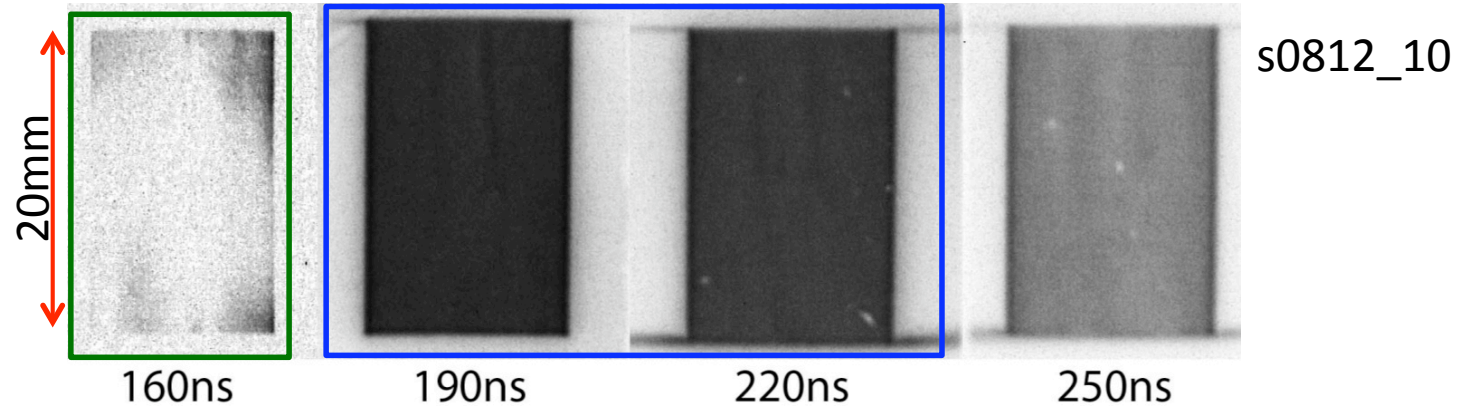
14mm

Liner

Conducting silver paint

Epoxy
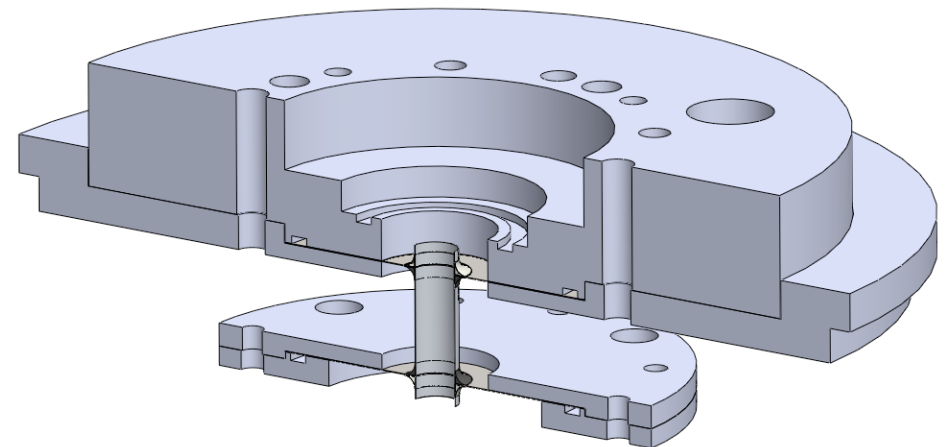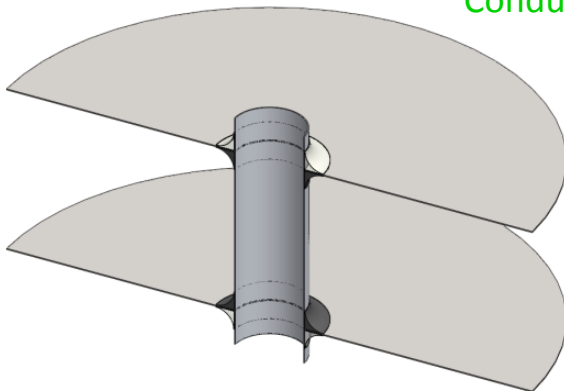
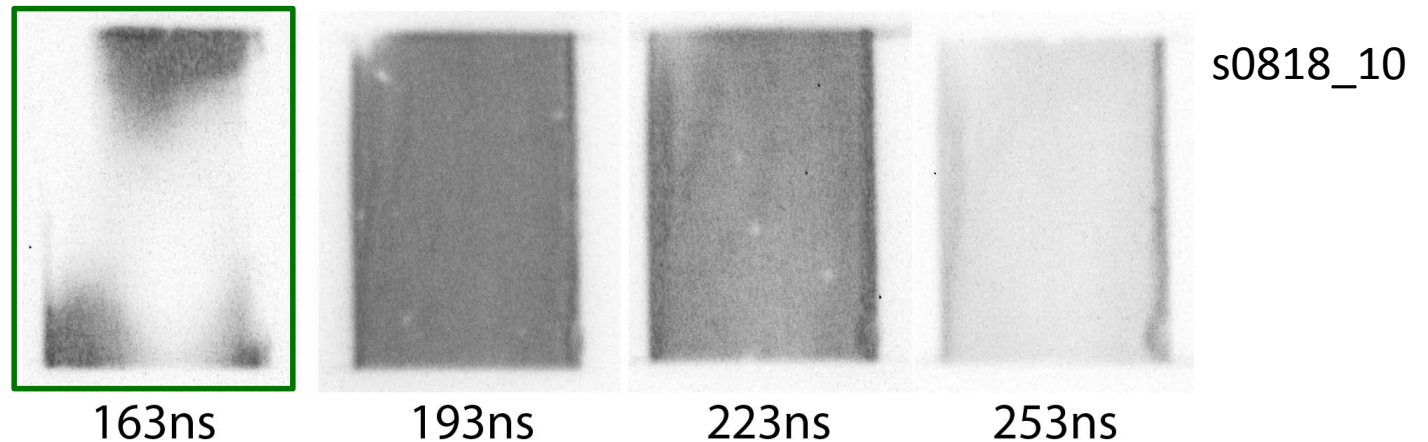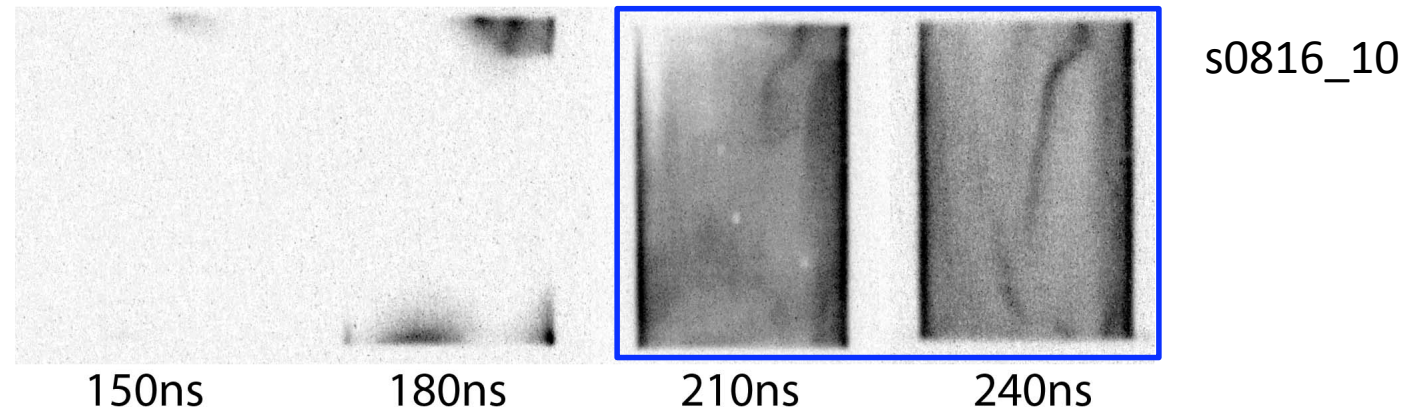# Imaging the outside surface of liners

XUV pinhole images
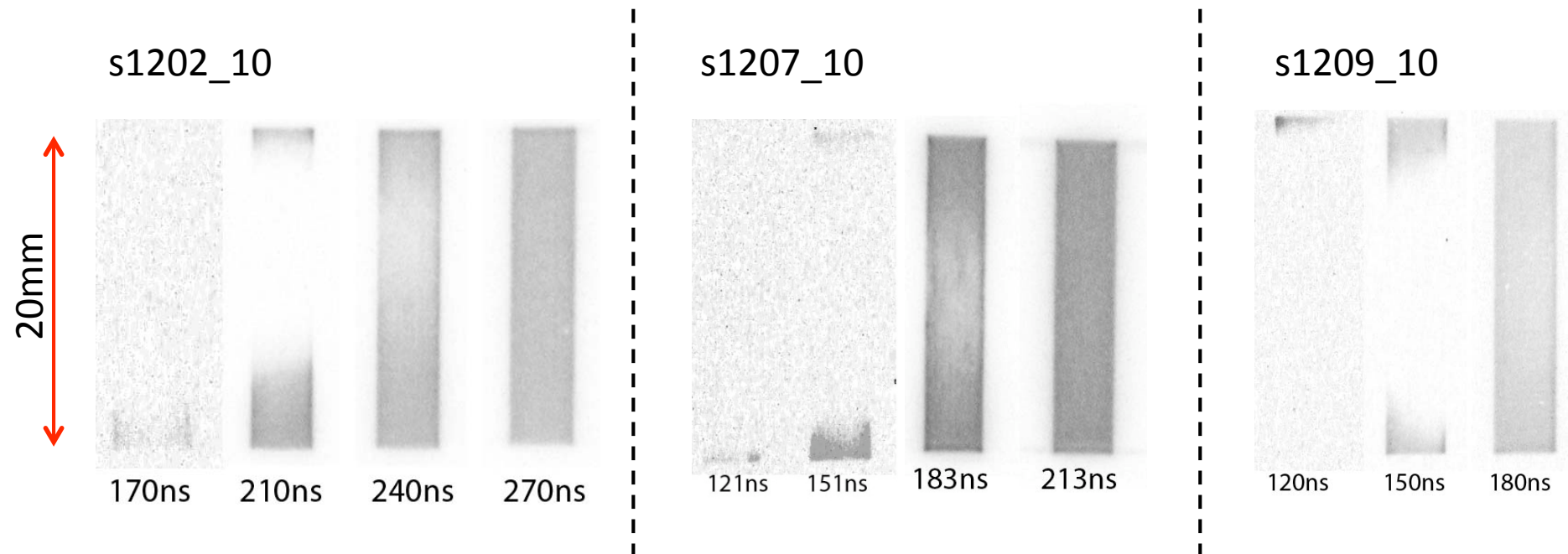
20um wall
homemade Al liners

20mm

Start-up at both ends

Striation often seen on
homemade liners

160ns   190ns   220ns   250ns

s0812_10

150ns   180ns   210ns   240ns

s0816_10

163ns   193ns   223ns   253ns

s0818_10

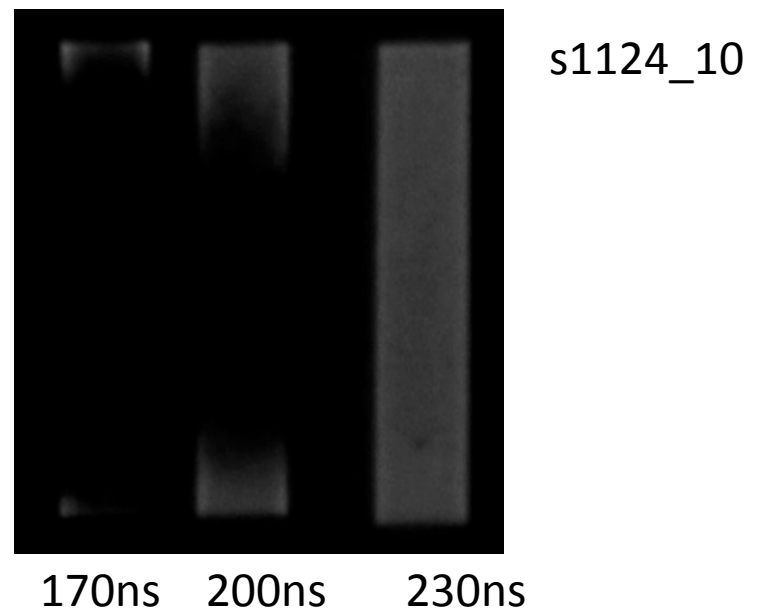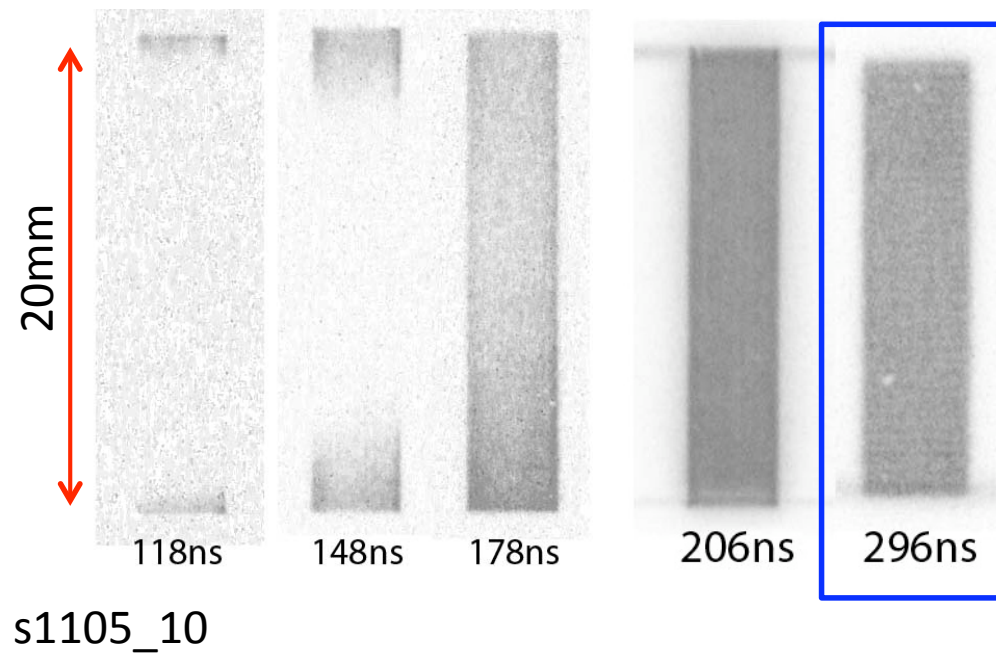# Imaging the outside surface of liners

XUV pinhole images

50um wall, 3.6mm OD Ni liners

Imaging the outside surface of liners

s1105_10

20mm

118ns   148ns   178ns   206ns   296ns

s1124_10
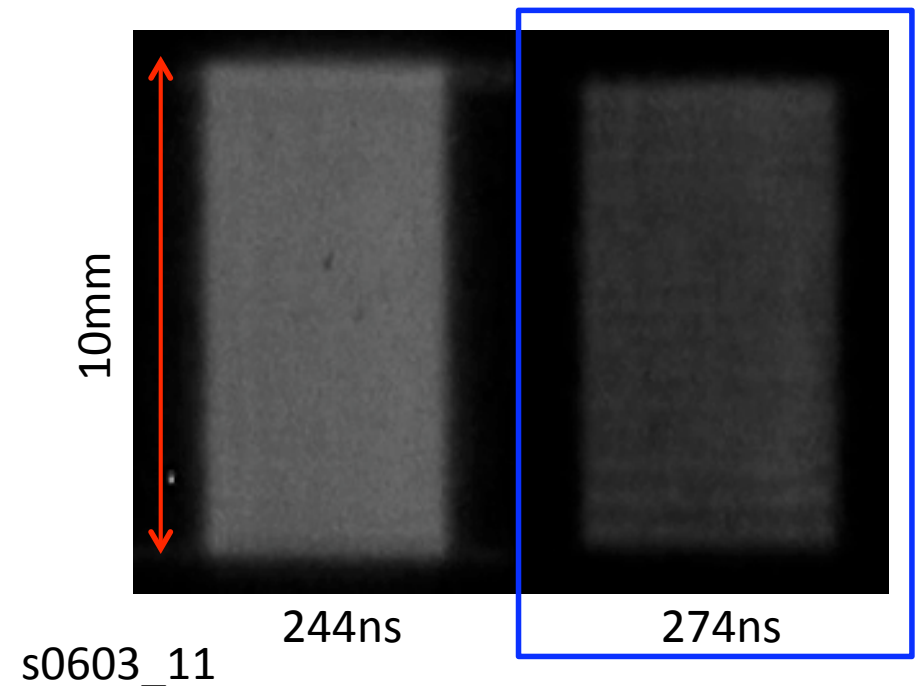
170ns   200ns   230ns

10mm

244ns   274ns

s0603_11

No anode-cathode asymmetry

Typically Ni liners light up 30ns earlier than Al liners

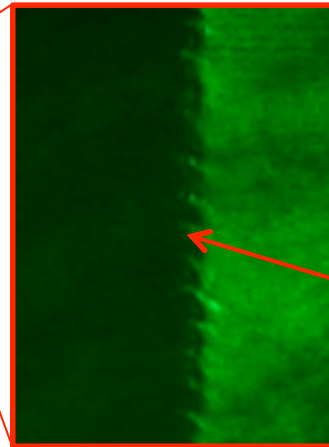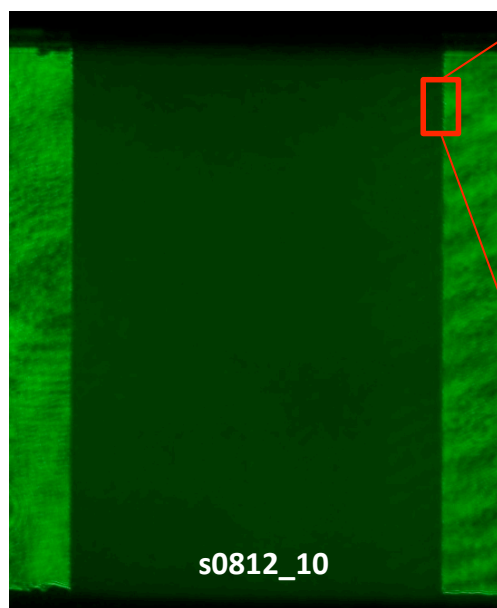Correlated azimuthal striations seen on Ni liners at late times

No XUV emission from 80um wall Al liners

Imaging the outside surface of liners
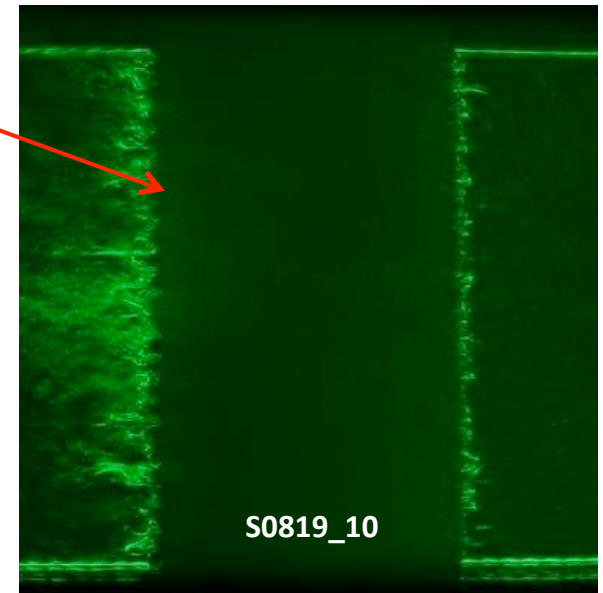
Laser probing of 20um wall aluminium liners

14mm diameter
Shadowgraphy 167ns

10mm diameter
Schlieren 298ns

Seam position

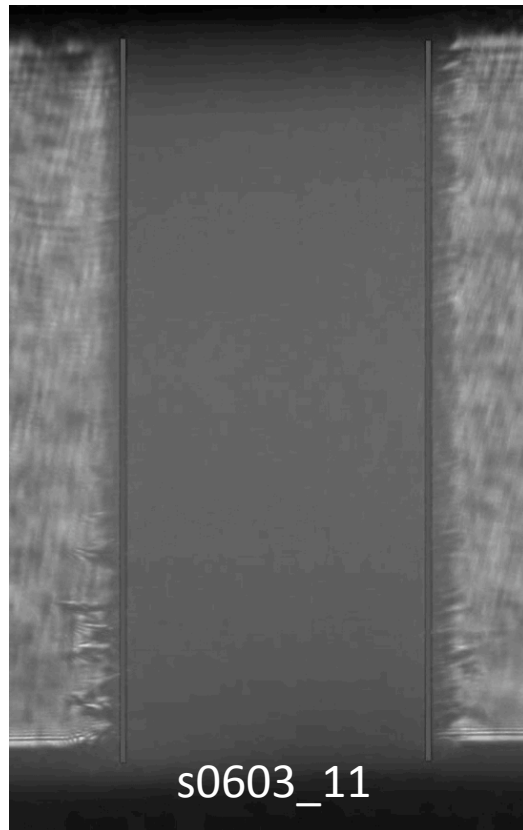l ≈ 170um
A ≈ 110um

s0812_10

S0819_10

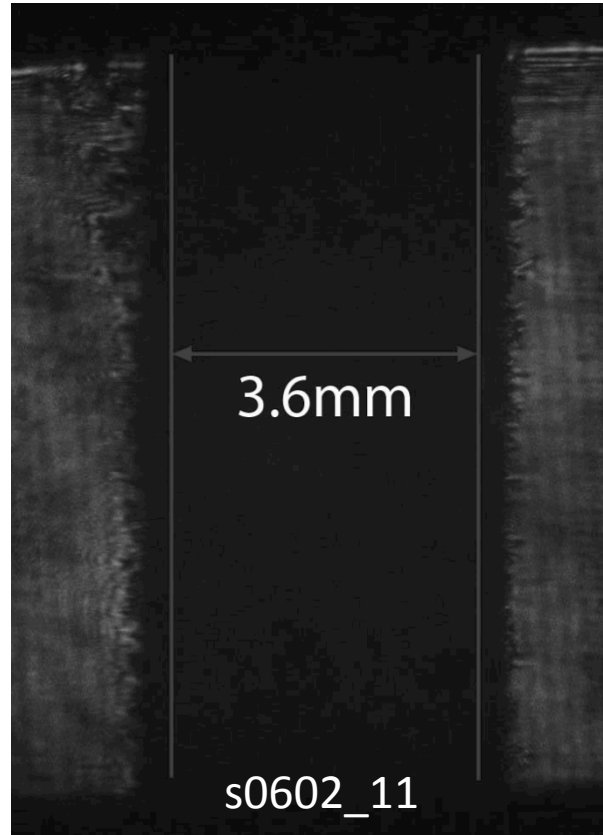Small instabilities seen on surface of 20um aluminium liners

No plasma seen on outside of 80um aluminium liners
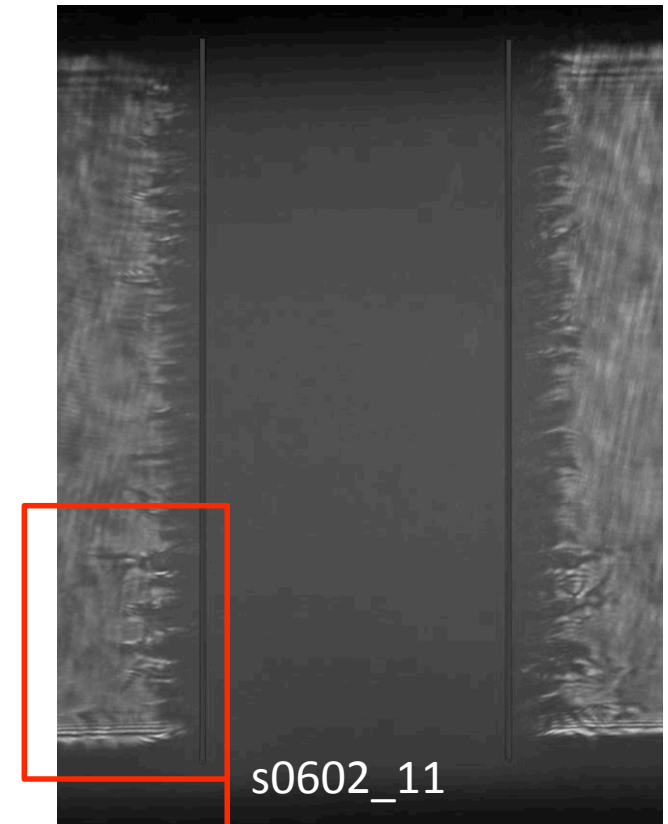
Imaging the outside surface of liners

Shadowgraphy of 50um wall nickel liners

169ns

227ns

247ns

Amplitude of instabilities grows at 10-15 km/s

Expansion velocity corresponds to ZT_e = 2-4 eV

l = 300-400 um
Amplitude = 0.7-1.0 mm

Liner parameters

	Ni 50um wall, 3.6mm OD	Al 20um wall, 14mm OD	Al 80um wall, 6mm OD
Resistivity (nΩm)	69.3	28.2	28.2
Skin depth (um)	90	60	60
Cross section (mm^2)	0.56	0.88	1.5
Mass per unit length (g m^{-1})	5	2.4	4
Melting point (K)	1728	933	933
Boiling point (K)	3186	2792	2792
Heat capacity (J mol^{-1} K^{-1})	26	24	24
Peak B field (T)	155	40	93